Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION	1b RESTRICTIVE MARKINGS
AD-A206 171	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; Distribution unlimited
4 PERFORMING ORGANIZATION REPORT NUMBER(S) AFGL-TR-89-0074	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION Air Force Geophysics Laboratory — 6b OFFICE SYMBOL (If applicable) OPA	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code) Hanscom AFB Massachusetts 01731-5000	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION — 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62101F	7670	15	16

11 TITLE (Include Security Classification) On the Scaling of Atmospheric Aerosol Scattering and Extinction With Wavelength

12 PERSONAL AUTHOR(S)
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13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
REPRINT	FROM ____ TO ____	1989 March 9	8

16 SUPPLEMENTARY NOTATION * Technion-Israel Inst of Technology, Haifa, 32000, Israel
Reprinted from Aerosols & Climate, pp 165-173, Peter V. Hobbs & M. Patrick McCormick, eds, 1988

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Atmospheric aerosols; Ultraviolet
			Extinction; Mie theory
			Scattering

19 ABSTRACT

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20 DISTRIBUTION/AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	Unclassified

22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c OFFICE SYMBOL
Eric Shettle		AFGL/OPA

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

AFGL-TR-89-0074

ON THE SCALING OF ATMOSPHERIC AEROSOL SCATTERING AND EXTINCTION WITH WAVELENGTH

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ABSTRACT

The possibility of relating the scattering or extinction by atmospheric aerosols at one wavelength to the scattering or extinction properties at another wavelength by scaling laws is examined. These scaling laws were tested using numerical simulations on representative models of the atmospheric aerosols and Mie theory calculations of their expected scattering and extinction properties. The simulations showed that forward scattering at fixed angles in the near-ultraviolet spectral region could provide useful predictions of near-infrared extinction. A good correlation is also presented between calculated forward scattering for a wavelength of 0.25 μm and backscattering at a wavelength of 1.06 μm. In a comparison of the 10.6 μm extinction with backscattering at 10.6 μm and with extinction at a wavelength of 1.06 μm, both showed too much scatter to develop useful scaling laws in those cases.

1. INTRODUCTION

This work will examine the possibility of inferring aerosol extinction at one wavelength directly from the angular scattering by the aerosols at another wavelength. In particular we will examine the use of forward scattering data in the ultraviolet (UV), such as that obtained by the instrument described by Trakhovsky & Shettle (1986), to determine the extinction in the infrared (IR). It is possible to invert the forward scattering as a function of angle to obtain the aerosol size distribution (see Trakhovsky & Shettle, 1985), which can be used in Mie scattering calculations to determine the extinction or scattering at any other wavelength. However, if the desired end result is the extinction at a few selected wavelengths, it is more efficient to directly calculate the desired extinction scaling laws, (assuming suitable laws can be derived).

A number of such scaling laws have been derived in the literature. Examples include Angstrom's (1929) classical power law for the wavelength dependence of extinction in the visible and near infrared, relationships between aerosol mass concentration and visible

ISBN 0-937194-11-5

(Charlson et al., 1968) or IR extinction (Pinnick et al., 1979), and the relationship between atmospheric backscattering and extinction (Curcio & Knestrick, 1958). Gerber (1985) recently discussed a number of such scaling laws, relating different visible or near-IR scattering measurements to IR extinction. It should be recognized that it is not always possible to develop scaling laws relating two specific aerosol properties such as visible and IR extinction because they may depend on aerosol properties that are only weakly correlated, such as the concentrations of small and large aerosols.

While scaling laws cannot be rigorously derived, an approximation relating the optimal scattering angle for predicting the extinction to given wavelengths for extinction and scattering will be shown. The scaling laws developed below were tested in a series of numerical simulations using various models of the atmospheric aerosols and calculations of their expected scattering and extinction properties.

2. THEORY

One of the results of Gerber's (1985) work is that a scaling law can be developed relating two parameters, if the kernels relating the parameters to the aerosol size differ by at most a multiplicative factor over most of the significant size range of the aerosol particles. This suggests that in developing scaling laws, we look for parameters whose kernels have similar dependences on aerosol size, where the scattering or extinction kernels are the scattering or extinction per unit volume as a function of size.

The optical theorem of quantum mechanics or the "extinction" theorem of van de Hulst, 1957, (also see Bohren & Huffman, 1983) implies that extinction is directly related to the scattering amplitude at a 0° scattering angle. Therefore the extinction can be measured and accounted for in two ways:

1) extinction = total angular scattering + absorption,
2) extinction is proportional to angular scattering at 0°.

Unfortunately it is experimentally impossible to distinguish between the incident unscattered and light scattered at 0°, therefore the optical theorem cannot be directly utilized. However, the forward scattering is a function of the ratio of the scattering angle and the wavelength (see van de Hulst, 1957). Therefore it is possible to scale the scattering kernel for two angles using two appropriate wavelengths. Combining this feature with the optical theorem it might be possible to deduce the extinction at one wavelength using the scattering measurement at another for some specific angle.

Using the above considerations, we will develop a relationship to predict the optimum scattering angle to use for a scaling law relating the extinction at a desired wavelength to the angular scattering at another wavelength. Using the anomalous diffraction approximation for the extinction kernel, γ, and the Fraunhofer diffraction approximation for the forward-scattering kernel, β,

(van de Hulst, 1957), a relationship can be derived between the wavelengths for the extinction (λ_1), and the scattering (λ_2), and the scattering angle (see Trakhovsky and Shettle, 1987 for details):

$$\sin \theta = 0.928\ (n-1)\ (\lambda_2/\lambda_1) \tag{1}$$

For λ_2 = 0.25 μm, λ_1 = 1.06 μm, and n = 1.33 we obtain θ = 4.14°. Figure 1 shows a comparison between the anomalous diffraction kernel at a wavelength of 1.06 μm and the Fraunhofer diffraction kernel at a wavelength of 0.25 μm and an angle of 4.14°. It is seen that agreement is good for the main lobe. This suggests that the above relationship could be used as the first guess of the optimal scattering angle in order to scale the extinction coefficient.

3. SCALING RELATIONSHIPS

Numerical simulations were performed to examine the validity of different scaling laws. Optical properties such as extinction, forward scattering, and backscattering were calculated using the aerosol model data base compiled by Shettle and Fenn (1979). The data base consists of five different aerosol models: tropospheric, rural, urban, maritime, and fog. For all the models but the fog, the calculations were made for relative humidities of RH=0%, 50%, 70%, 80%, 90%, 95%, 98%, and 99%. In addition 4 different types of fog are presented. In doing the numerical simulations, 3 different total number densities were used for each model, for a total of 108 data points. These number densities were the ones used by Shettle & Fenn (1979), and those values increased and decreased by a factor of 2 to represent a range of atmospheric conditions.

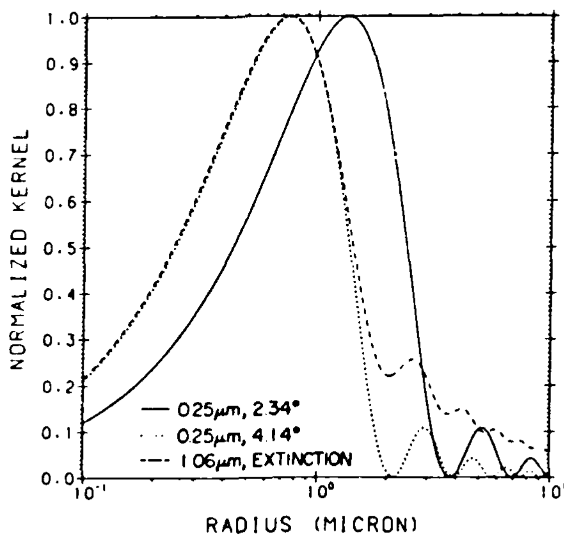

FIGURE 1. A comparison of diffraction kernel for 4.14° at 0.25 μm with the approximate extinction kernel at 1.06 μm. Also shown is the diffraction kernel at 2.34° and 0.25 μm.

In deriving the scaling laws presented below, a quadratic regression equation (in log-log space) of the form:

$$\log \gamma(\lambda_1) = a_0(\theta) + a_1(\theta)\log \beta(\lambda_2,\theta) + a_2(\theta)\log^2 \beta(\lambda_2, \theta), \quad (2)$$

was fit to the model calculations of γ and β. The "best fit" scattering angle, θ, was the angle for which the rms deviation of $f(\log \beta)$ from $\log \gamma$, (over the 108-modeled data points), was a minimum.

3.1 FORWARD-SCATTERING/EXTINCTION

Forward-scattering/extinction-scaling relationships were investigated for λ_2 = 0.25 µm and λ_1 =1.06 and 3.75 µm. The relationship Eq. (1), was used to determine the approximate location of the best fit angle. Then the angle was varied to determine the one that gives the best fit of the data points to a second degree polynomial in log-log space. The rms deviation of the best fit polynomial from the simulated data points is a weak function of the scattering angle and typically is less than 20% smaller at the best fit angle than at the initial angle given by Eq.(1), even though the angles often differ by a factor of two.

Figure 2 shows the angular scattering at an angle of 2.34° for a wavelength of 0.25 µm versus the extinction at the wavelength of 1.06 µm. This angle is shifted from the first-guess angle of 4.14°, because the exact Mie angular-scattering kernels are different from the approximate diffraction form. This can be seen by comparing the kernels in Fig. 3 with those in Fig. 1. The MIE angular-scattering kernel deviates significantly from the diffraction approximation, especially for the smaller particles. The anomalous diffraction approximation reproduces the exact Mie extinction quite well.

The data points in Fig.2 can be fitted using the following scaling relationship:

$$\log \gamma_1 = -1.07 + 0.94 \log \beta_2 + 0.107 \log^2 \beta_2 \quad (3)$$

The rms deviation between the data points and the fitting curve (Eq. 3) is 35% over 5 orders of magnitude.

A similar least squares fit was carried out for forward scattering at 0.25 µm vs. extinction at 3.75 µm. The minimum rms deviation was found for a scattering angle of 0.57°. The data points can be fitted using the following scaling relationships:

$$\log \gamma_1 = -2.31 + 1.07 \log \beta_2 - 0.019 \log^2 \beta_2 \quad (4)$$

The rms deviation between the data points and Eq. (4) is 32% over 6 orders of magnitude. As with the 1.06 µm case, the angle for the best fit is shifted from the 1.17° predicted by Eq.(1).

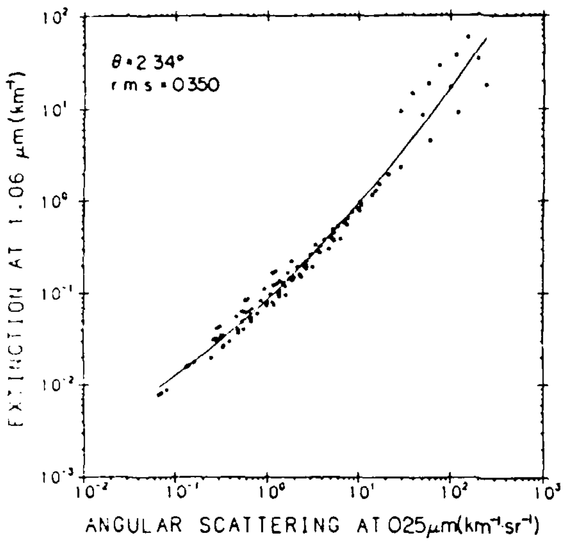

FIGURE 2. A correlation between extinction at 1.06 μm and angular scattering for 2.34° at 0.25 μm.

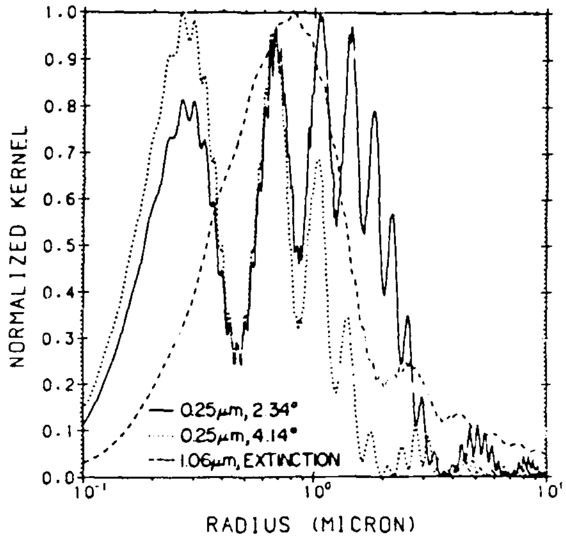

FIGURE 3. A comparison of the Mie angular-scattering kernel for the angles 2.34° and 4.14° at 0.25 μm and the Mie extinction kernel at 1.06 μm.

3.2 FORWARD-SCATTERING/BACKSCATTERING

The forward-scattering/backscattering relationship was investigated for the wavelengths of 0.25 and 1.06 μm. A least squares procedure was carried out varying the forward-scattering angle to find the minimum rms deviation from a quadratic function in log-log space as with the extinction and forward scatter. It was found that the best fit is obtained for the angle of 1.02°, which is shown in Fig. 4. The data points can be fitted using the following scaling relationship:

$$\log\beta_1 = -3.05 + 0.70 \log\beta_2 + 0.100 \log^2 \beta_2 \qquad (5)$$

The rms deviation between the data points and the fitting curve is 37% over 5 orders of magnitude.

3.3 BACKSCATTERING/EXTINCTION

The correlation between backscattering and extinction at the same wavelength is a critical assumption in the inversion of lidar measurements to obtain extinction data (Klett, 1985). The degree of this correlation for a wavelength of 10.6 μm is examined in Fig. 5. While there is a positive correlation, there is also a large scattering of the results, so the best fit curve through the data points will only predict the extinction from the backscattering within a factor of five. Pinnick et al. (1983), found a similar limited correlation at 10.6 μm, restricting their calculations to water clouds, which correspond to the upper right-hand corner of Fig. 5.

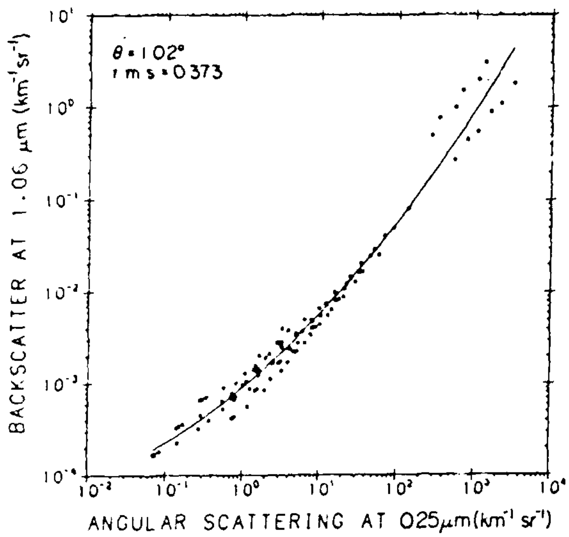

FIGURE 4. A correlation between backscattering at 1.06 μm and angular scattering for an angle of 1.02°.

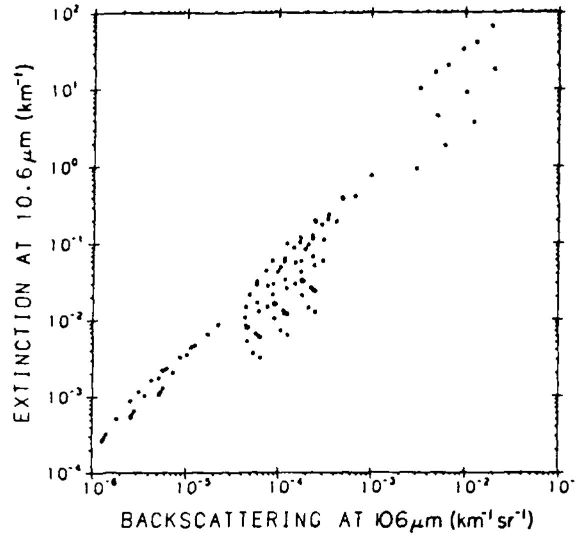

FIGURE 5. A correlation between extinction and 10.6 μm and backscattering at 10.6 μm.

3.4 EXTINCTION/EXTINCTION

The possibility of developing a scaling law relating the extinction at two different wavelengths was investigated for the wavelengths of 1.06 and 10.6 μm. The resulting scatter-plot is shown in Fig. 6. It is clear that the correlation is poor. This might be expected since extinction at a given wavelength is most sensitive to particulate size ranges that are similar to the wavelength. Angstrom's power law for the wavelength dependence works well because it is restricted to the visible, and the sensitive size ranges differ by a factor of about two. Also the size ranges fall within the accumulation mode and so can be expected to be reasonably correlated. Whereas, the 10.6-μm extinction is much more sensitive to the coarse mode particles, which are not necessarily well correlated with the accumulation mode aerosols, since in general they represent different sources.

4. DISCUSSION

In this paper several possible scaling laws have been examined with mixed results. Good correlations were found between calculated values of forward scattering and calculated values of extinction for a wide range of model parameters, provided suitable angles for the scattering were considered.

A first-guess approximation relating the optimal scattering angle, for predicting the extinction, to given wavelengths for the scattering and extinction was developed. The derivation of this approximation was based on the diffraction approximation to the exact Mie scattering kernel. This approximation does not take into account the wave interference between the transmitted and diffracted light,

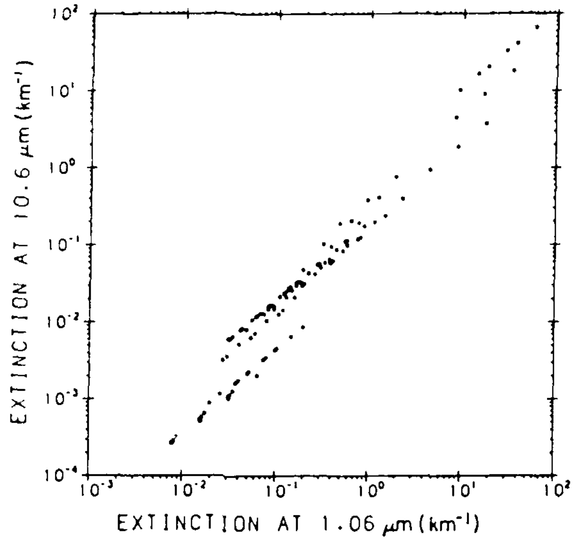

FIGURE 6. A correlation between extinction at 10.6 μm and extinction at 1.06 μm.

which results in the oscillatory behavior of the exact kernel. Therefore, the predicted scaling angle deviates from the optimal angle deduced using the Mie calculations.

A useful scaling relationship between simulated forward scattering at 0.25 μm and backscattering at 1.06 μm was also derived. Attempts to find scaling laws relating simulated 10.6-μm extinction with either backscattering at 10.6 μm or with extinction at 1.06 μm were less successful.

It might be noticed that the scaling laws derived were nearly linear on a log-log plot. This linearity is not surprising and if a wider range of number densities were included in the model calculations the linear behavior might be stronger. This behavior occurs if only the total number of particles is varied while holding the relative number for each size fixed, then the extinction or scattering at a given angle will both vary in direct proportion to the total number of particles. Thus on a plot such as Figure 2 or Figures 4-6, varying the total number density while holding all else fixed, would lead to families of data points along 45-deg straight lines. Concern for artifically producing such linearities limited the range of number densities to that required to produce realistic variations in seeing conditions. The resulting meteorological ranges, varied from 0.07 to nearly 1.0 km for the fogs, and from about 1.0 km for the urban model at 99% relative humidity and maximum number density, to 115 km for the tropospheric model at relative humidity and minimum number density.

In conclusion it should be recognized that the scaling laws discussed in this paper were developed on the basis of calculations using models of the atmospheric aerosols. These scaling laws rigorously apply only to the models used in developing them; they apply to the real world only to the extent that the properties of the models accurately represent the real world, (see Shettle et al., 1984, for a comparison of the models with scattering measurements). Recently Gerber (1987) has presented experimental verification of some scaling laws (relating forward scattering at 0.63 μm to IR extinction) similar to those discussed in the present paper.

ACKNOWLEDGMENTS

The present study was conducted while E. Trakhovsky was at the Air Force Geophysics Laboratory (AFGL) under a National Research Council (NRC) Research Associateship. He is grateful to both the NRC and AFGL for their support.

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